REMR Technical Note CS-ES-4.3

Stability of Existing Concrete Structures

Introduction

Older navigation and flood-control structures that have performed satisfactorily are now being examined to determine if rehabilitation is required to meet stability criteria. A common procedure for evaluating the safety of these structures is the conventional equilibrium method of analysis, which is based largely on classical limit equilibrium analysis without regard to deformation. Today, analytical tools such as the finite element method (FEM) are available and can be used to consider the manner in which loads and resistance are developed as a function of the stiffness of the foundation rock (or soil), stiffness of the structure, and the structure-to-foundation interface.

Two procedures formulated using the FEM are being employed to evaluate the conventional equilibrium method. The results of a study using these two procedures to analyze an existing earth-retaining structure along with the results from the conventional equilibrium method are presented to show the similarities in the two FEM procedures and the differences between them and the conventional equilibrium method.

Modeling Loss of Contact Along the Interface Using the FEM

Recent research efforts have been directed toward developing analytical procedures using the FEM analysis for problems concerned with loss of contact between the base of a gravity wall and its foundations. This situation arises when structures are loaded so heavily that a gap develops in the interface region. Two approaches have been used to analyze this type of problem: one involving the modeling of a predetermined plane along which separation is presumed to develop using interface elements and the other involving the use of fracture mechanics concepts.

Base separation analysis using interface element

The FEM program SOILSTRUCT was expanded during phase I of the REMR Research Program to model the loss of contact between the base of a gravity wall and its foundation using a procedure called the Alpha method (Ebeling, Duncan, and Clough 1990; Ebeling, Clough, Duncan, and Brandon 1992). SOILSTRUCT is a general-purpose FEM program for two-dimensional

(2-D) plane strain analysis of soil-structure interaction problems. It calculates displacements and stresses due to incremental construction and/or load applications and can model nonlinear stress-strain material behavior. Two types of finite elements are used to represent the behavior of different materials comprising the monolith, its rock foundation, and the interface between them: a 2-D continuum element and an interface element.

During each incremental following load analysis, each interface element along the base of the wall is checked to detect tensile stress at its center. If none is found, the following load analysis proceeds as usual. When tensile stresses are observed in the interface elements, the incremental analysis is repeated using the Alpha method. Briefly, the principle of the procedure is to: (a) factor the applied incremental load vector so that zero normal stress will result at the center of each of the interface elements which previously developed tensile stress at its center, (b) make the interface stiffness equal to zero, (c) convert the shear stress regime into an equivalent set of nodal point forces, (d) transfer this equivalent force into adjacent elements by applying it as an external force at the nodes, and (e) maintain equilibrium by subtracting the equivalent internal stress from within the interface element(s) used to formulate this force. The procedure is repeated until the total initial load increment has been applied.

Linear elastic fracture mechanics - discrete crack

A second FEM-based procedure for modeling crack development at the base of an earth-retaining structure in a following load analysis uses fracture mechanics concepts. Generally, linear elastic fracture mechanics (LEFM) relate the stress magnitude and distribution at the crack tip to the nominal stress applied to the structure; to the size, shape, and orientation of the crack or discontinuity; and to the material properties. The "demand" due to the loading(s) applied to the retaining structure, and specifically to the region of cracking, is represented by stress intensity factors, K_I, K_{II}, and K_{III} for three cracking modes. Cracking Mode I is an opening mode, Mode II is a shearing mode, and Mode III is a tearing mode.

Conceptually, the stress intensity factors indicate the rate at which the stress approaches infinity ahead of the crack tip for each of the three displacement modes. The stress intensity factors characterize the magnitude of the crack tip stress field for the potential cracking modes. The "capacity" of the material is characterized by the fracture toughness, K_c. Crack advance is monitored in an LEFM analysis by comparing the demand to capacity (e.g., K_I to K_{Ic}). The special-purpose FEM code MERLIN (Reich, Cervenka, and Saouma 1991) was used to perform the LEFM analysis for this study.

Description of the Lock Wall

Figure 1 shows a typical cross section for an existing lock wall. The wall is idealized as a 34.5-ft-long, 45-ft-wide (at the base) and 92-ft-tall massive concrete monolith retaining 83.7 ft of backfill with a water table 56 ft above the base.

Load Applied to the Lock Wall

In order to make a direct comparison between the conventional limit equilibrium method and the two finite element methods, it was assumed that the wall was loaded by a predefined lateral pressure of given magnitude and distribution, as shown in Figure 1. Lateral pressures were established using conventional concepts for earth and water loadings on retaining wall systems and were applied to the wall in a series of steps to determine the response of the structure to gradually increasing loads. Therefore, the magnitudes and distributions of the loadings were uncoupled from the action of the wall-foundation system. This form of loading is termed "following load analysis."

At-rest earth pressures were assigned normal to the plane extending vertically from the heel of the wall through the backfill (Figure 1). Lateral earth pressures corresponded to an at-rest earth pressure coefficient K_o of 0.45. A vertical shear force (also referred to as a downdrag force) was assigned to this plane. A shear force corresponding to a vertical earth pressure coefficient K_v of 0.09 was assigned in all analyses.

The monolith and foundation were assumed to be impervious. Water flow from the backfill to the pool in front of the monolith was confined to the interface between the base of the monolith and the foundation. A linear head loss was assigned to this interface region where the monolith retained contact with the foundation. For the interface region where the monolith had separated from its foundation, hydrostatic water pressures corresponding to the hydrostatic head within the backfill were assigned. In the FEM analyses, water pressures were assigned along the interface, as shown in Figures 1 and 2.

Computed Results from Three Methods

Results of the following load analyses are summarized as follows:

a. *Conventional equilibrium analysis (CEA).* Using the assumed linear compressive effective stress distribution directed normal to the base, the conventional equilibrium method of analysis resulted in a base area B_e in compression of 22.92 ft, or 50.9 percent of the base area in compression (B_e/B). This does not meet the design requirement of

75 percent for new structures of this type subjected to an extreme loading (i.e., a dewatered lock).

b. *Base separation analysis using interface elements.* The value for B_e computed using the finite element analysis (FEA) with interface elements was 32.65 ft, or 72.5 percent of the base area in compression. Figure 3 shows the normal effective stress distribution along the interface computed using both the FEA with interface elements and the equilibrium method of analysis. The resulting normal effective stress distribution from the FEA is distinctly nonlinear. The maximum normal effective pressure computed at the toe was 70,698 psf by the FEA method and 36,343 psf by the CEA method.

c. *LEFM analysis.* An LEFM analysis of wall was conducted using MERLIN (Headquarters, Department of the Army 1993) for the same lateral following earth and water loadings used in both the conventional equilibrium method of analysis and in the FEM analysis using SOILSTRUCT. The material toughness K_{Ic} was set equal to zero along the interface between the monolith and the foundation. Uplift pressures were applied along the base as described previously. A series of six analyses, each with a different specified crack length, was performed using MERLIN to obtain an estimate of the crack length. The specified crack lengths for these analyses ranged from 6.0 to 13.5 ft in 1.5-ft increments. A crack length of 12.99 ft was estimated by interpolation of results of K_1 for the analysis with a crack length of 12 ft and the analysis with a crack length of 13.5 ft. Additional analyses were performed with refined meshes to determine a precise value for the final crack length. This procedure was repeated until the value of K_1 was less than 0.001 ksi $[\text{in.}]^{1/2}$. The final crack length computed using this approach was 13.02 ft, corresponding to B_e of 31.98 ft (B_e/B = 71.1 percent).

Figure 3 shows the normal effective stress distribution along the interface computed using both the FEA with interface elements and LEFM. Both analyses resulted in nonlinear normal effective stress distributions that were similar in shape. The maximum normal effective pressure was 70,698 psf by the FEA with interface elements and 105,603 psf by the LEFM.

Figure 4 shows the shear stress distribution along the interface computed using both the FEA with interface elements and LEFM. Both analyses resulted in nonlinear shear stress distributions of similar shape.

Conclusions

The principal results of the three following load analyses of the lock wall were as follows:

a. The value of B_e/B computed using both FEM with interface elements (72.5 percent) was nearly equal to the value computed using LEFM (71.1 percent).

b. The values of B_e/B computed using both FEM analyses were significantly greater than the 50.9 percent computed using CEA.

c. Both FEM analyses resulted in nonlinear normal effective stress distributions, contrasting with the assumed linear stress distribution used in the CEA.

References

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Headquarters, Department of the Army. (1993). "Fracture mechanics analysis of a gravity lock monolith," ETL 1110-2-344, Washington, D.C.

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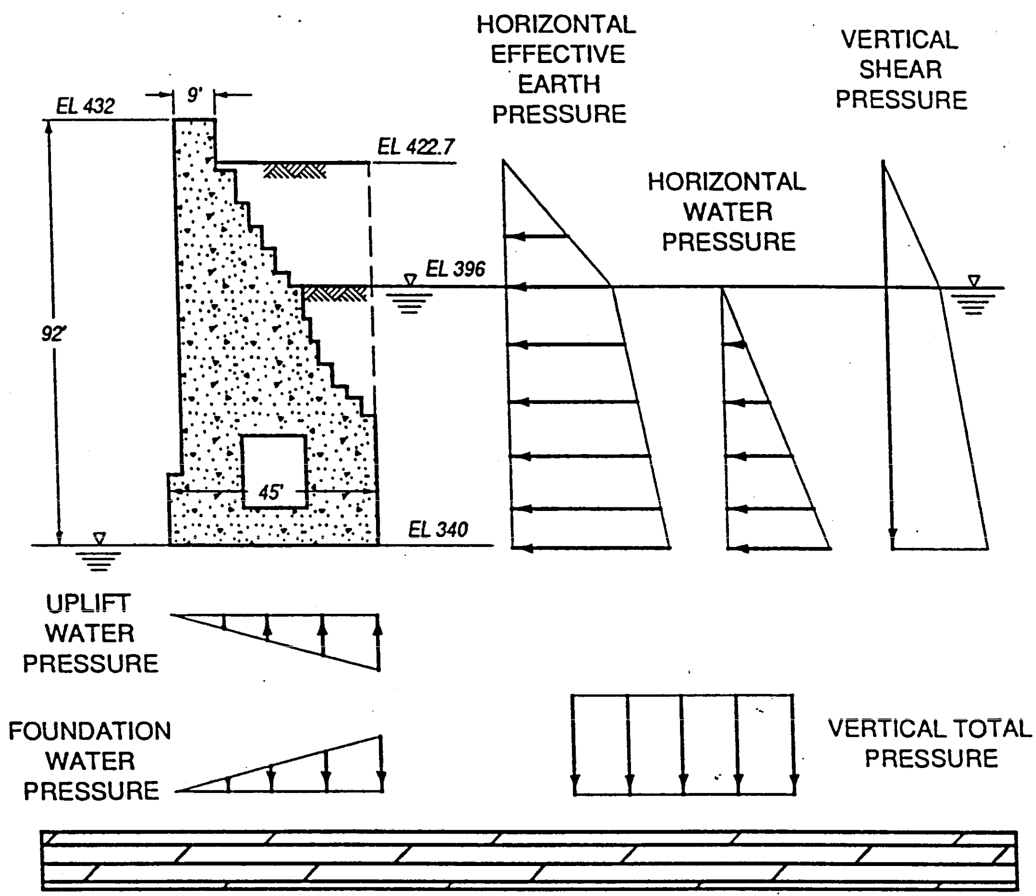

Figure 1. Cross section and following earth and water loadings

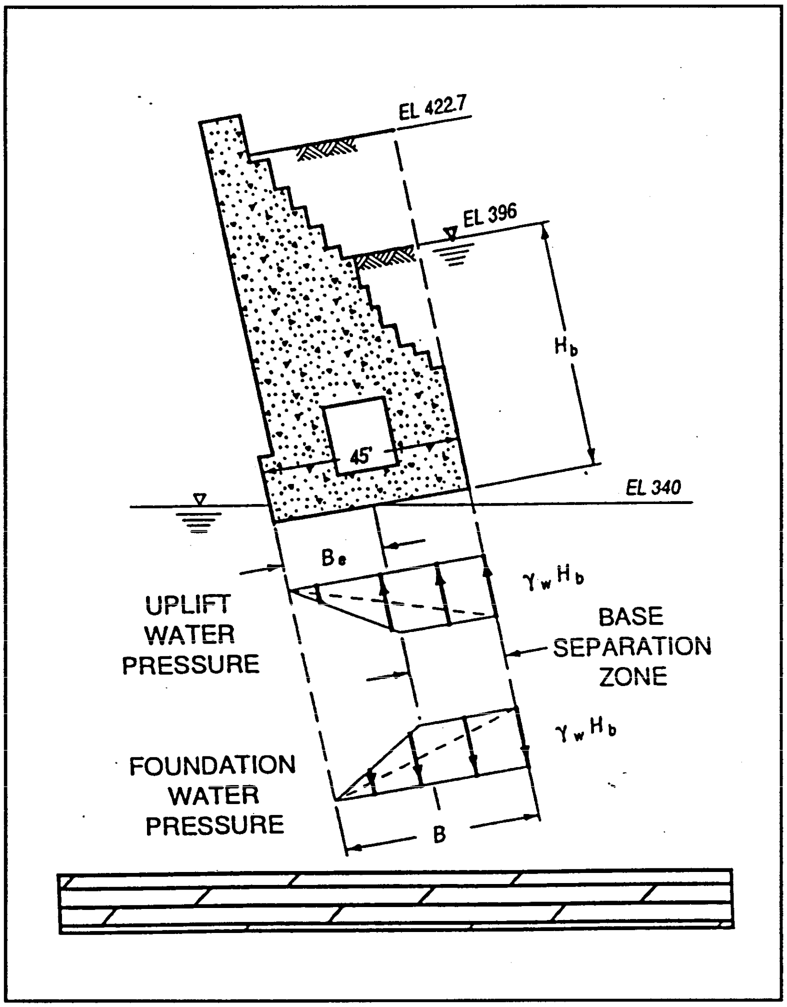

Figure 2. Water pressure distribution along the monolith to rock interface

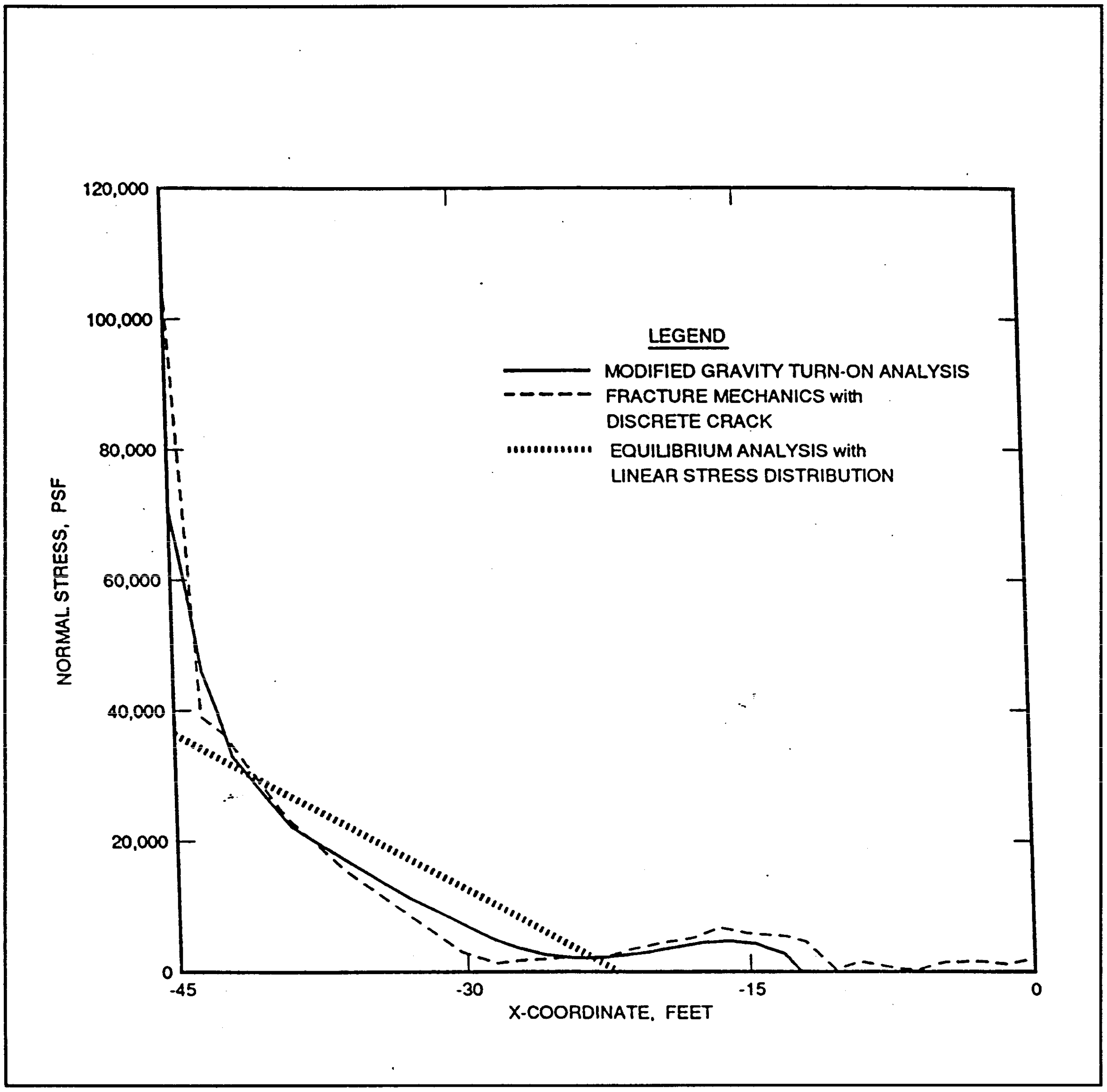

Figure 3. Normal stress distributions along the base of wall

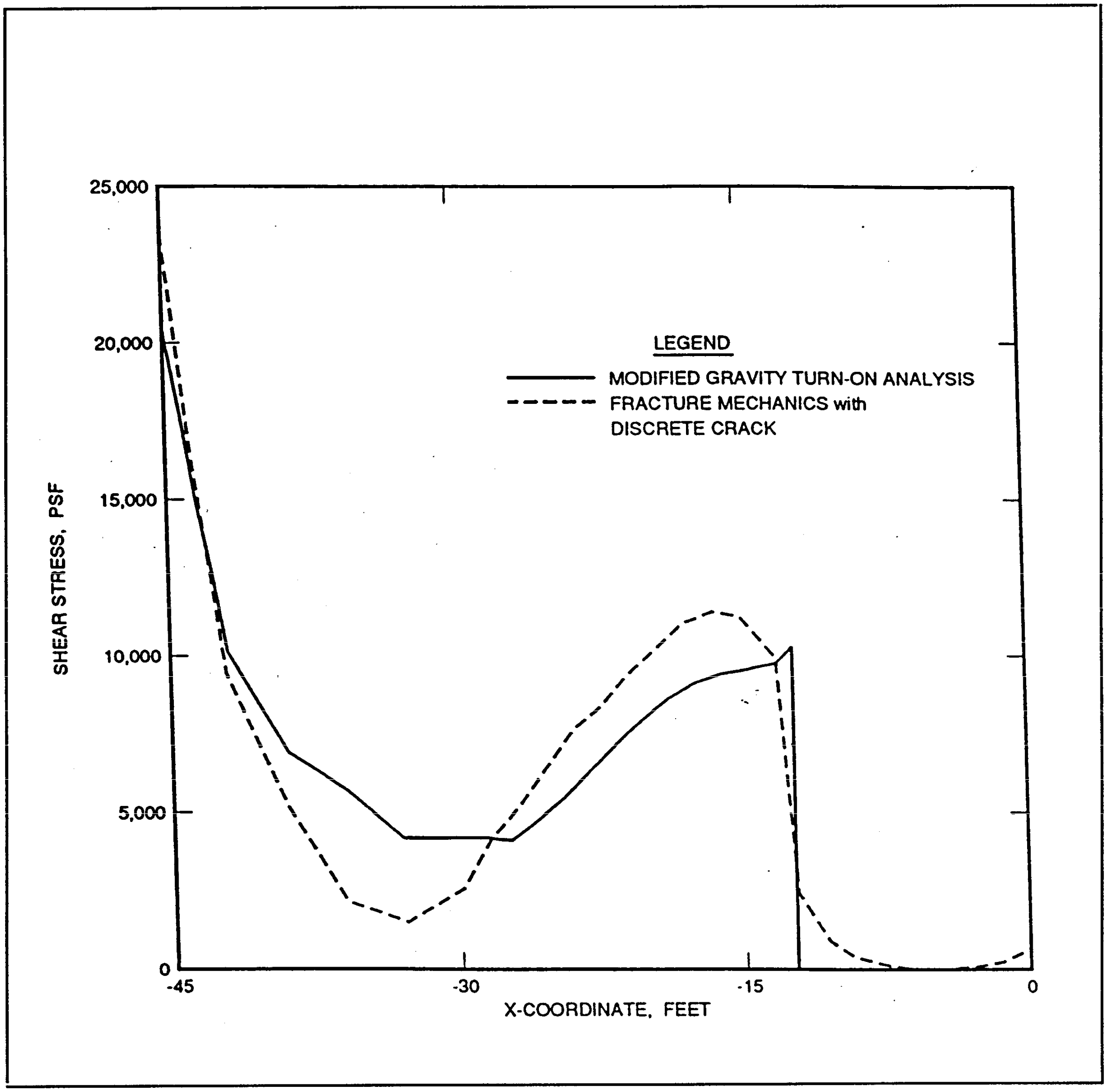

Figure 4. Shear stress distributions along the base of wall